Report to the Test Director

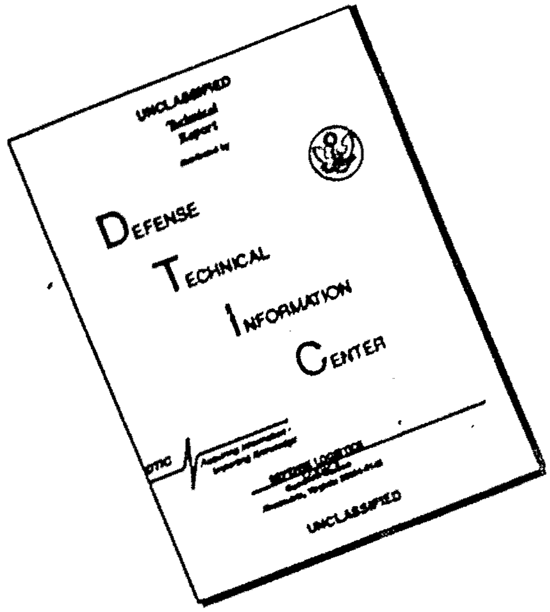
SURFACE MOTIONS FROM AN UNDERGROUND EXPLOSION

By

D. S. Carder
W. K. Cloud
L. M. Murphy
J. H. Hershberger

U. S. Department of Commerce
Coast and Geodetic Survey
June 1958

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

CONTENTS

TABLES

FIGURES

ABSTRACT

Seismic effects of Rainier, a 1.7-kt nuclear shot detonated 900 feet underground, were measured in terms of ground surface motion at ten strong-motion seismograph stations located 1200 to 45,000 feet from the source. In addition, records were borrowed from seven teleseismic stations located 100 to 300 miles from the source.

Recorded accelerations attenuated from a maximum single-component value of 2.6 g at 1280 feet to 0.009 g at 17,640 feet. Attenuation of acceleration out to 300 miles was in reasonable agreement with the empirical formula, $a = 25 \times 10^5/D^2$, where a = maximum single-component acceleration (g), and D = distance from source (feet). At all stations the ratio of "a" recorded to "a" computed was between the limits of 0.2 and 2.2. At 13 of the 17 stations the ratio was between the limits 0.34 and 1.8. At 7 of the 10 strong-motion stations the ratio was between the limits 1.0 and 1.8.

Amplitude attentuation is more complicated. Tentative empirical formulas are

$$A = \frac{0.7}{R^2} \quad \text{from 0.3 to 3 km}$$

$$A = \frac{0.32}{R} \times 10^{-0.006R} \quad \text{from 3 to 100 km}$$

$$A = \frac{0.0075}{\sqrt{R}} \times 10^{-0.0025R} \quad \text{from 180 to 1000 km}$$

where R is distance in kilometers and A is rest-to-peak ground amplitude in centimeters. All observed data fit these formulas within the limits 0.25 to 3 and all except 3 within the limits 0.5 and 2.

Gutenberg-Richter magnitude of Rainier, calculated as for a natural earthquake from seven Wood-Anderson seismograph records, was 4.6. For an earthquake, this magnitude would indicate energy radiated in the form of elastic waves in the range of 10^{18} ergs. Earthquakes of 4.6 magnitude, however, are felt up to 60 miles from the epicenter. Rainier was felt by only a few observers at 2-1/2 miles.

Using strong-motion data, seismic energy near the source was at least $10^{18.1}$ ergs and perhaps as high as $10^{18.6}$ ergs, which corresponds to a 4.9 magnitude earthquake. However, because of rapid attenuation near the source, seismic energy for comparison purposes with earthquakes was more nearly $10^{16.9}$ to $10^{17.4}$ ergs, which corresponds to a magnitude 4 earthquake.

Seismologists at established teleseismic stations, having been given time of origin and coordinates, were able to pick out Rainier's elastic wave signature on seismograms at considerable distance. For example, very small amplitude waves from Rainier were found on the Coast and Geodetic Survey, College, Alaska, seismogram, 3600 km away, although attempts in the eastern United States at distances of 2000 to 3000 km, using conventional instruments, were not successful.

ACKNOWLEDGMENTS

The authors wish to express appreciation to the following persons outside the Coast and Geodetic Survey who by their cooperation contributed much to the success of Project 26.4d.

Dr. R. G. Preston, Mr. Don Schueler, and Mr. Stanley E. Warner, University of California Radiation Laboratory.

Professor Perry Byerly, University of California.

Professor Frank Press, Professor D. E. Hudson, and Professor G. W. Housner, California Institute of Technology.

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The objective of Project 26.4d was to measure seismic effects in terms of ground surface accelerations and transient displacements resulting from Shot Rainier, a 1.7-kt nuclear explosion detonated 899 feet underground. Geographic range for the project was between 900 feet and several miles horizontally from a vertical line through zero, a range not covered by other participating agencies.

1.2 BACKGROUND

The primary consideration in connection with Shot Rainier was containment of radioactive materials. A secondary consideration was seismic effects. Seismic effects were not expected to be serious, but as a precaution and to provide for quantitative measurement, the Coast and Geodetic Survey was asked to monitor the shot. Instruments and methods used by the Survey in its normal strong-motion earthquake activities were considered suitable to perform the task demanded by Project 26.4d, namely, the measurement of ground motion in the acceleration range from 2 to 3 g, down to 0.001 g or less, and ground displacements of 3 inches or less.

CHAPTER 2

PROCEDURE

2.1 SHOT PARTICIPATION

Ten strong-motion seismograph stations were established at locations shown in Figure 2.1 (See Appendix, Table A.1, for coordinates and elevations.) Essentially each station consisted of an unreinforced concrete pier (or slab) well-bonded to a firm outcrop of local foundation material. With the exception of Station 5, which was in a tunnel above and to the south of the Rainier tunnel, all stations included light-tight shelters over the piers. Pictures of stations are shown in the Appendix, Figures A.1 and A.2.

Vertical, radial, and tangetial components of acceleration and transient displacement were measured at Stations 1 through 9. At Station 7.2a2 North, only the three components of transient displacement were measured.

2.2 INSTRUMENTATION

Instruments used on Project 26.4d, with the exception of vertical displacement components, were standard equipment of the type used for years by the Coast and Geodetic Survey to record strong earthquake motion. (Photographs of the equipment are shown in the Appendix, Figures A.1 - A.4.) Vertical displacement components were small disks mounted on pivot and jewel spindles. Offset weights on the rim determined effective pendulum lengths, coiled springs supplied balance and restoring force.

All instruments were direct-recording seismographs consisting of simply constructed compound pendulums damped by permanent magnets, together with timing clocks, and 12-inch photographic tape cameras. Direct recording was accomplished by means of optical styli (focused light beams reflected to the photographic paper from mirrors attached to pendulums near axes of oscillation). Shaking-table tests on the types of pendulums used have given results closely approximating theoretical for sustained simple harmonic motion. (See Reference 1.)

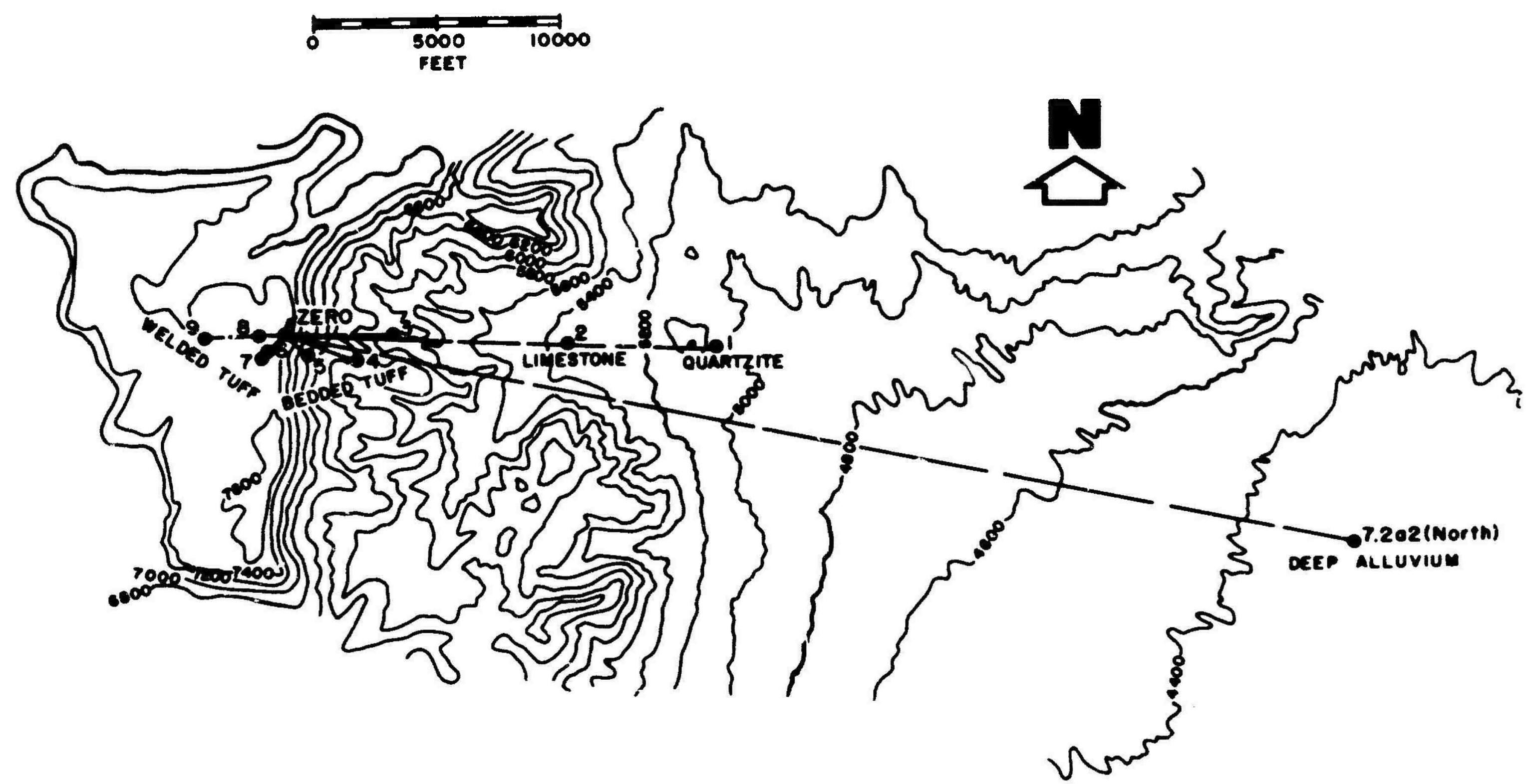


Fig. 2.1 Location of strong-motion seismograph stations for Project 26.4d.

As a partial check on instrument reliability during Rainier an indirect method was used. Acceleration as recorded on one component at Station 09 was fed as a voltage function to an electric circuit having period and damping characteristics of the accelerometer. Both voltage input (simulating ground acceleration) and voltage drop across the circuit inductance (simulating accelerometer response) were photographed on a dual beam oscilloscope. The results are shown in Figure 2.2, (a) being simulated ground acceleration and (b) being simulated accelerometer response.

2.3 EMPIRICAL FORMULAS

Due to the heterogeneity of materials in the Rainier area and lack of reliable information, the Survey approached the problem of predicting maximum surface accelerations and transient displacements empirically. The Survey's concern was primarily to develop scaling formulas that would indicate the range of seismometer sensitivities necessary to yield readable records.

The first assumption was that the ratio of maximum single-component accelerations for different weights of explosive and different distances from source might be predicted by the formula

$$\frac{a_2}{a_1} = \left(\frac{W_2}{W_1}\right)^{1/2} \left(\frac{D_1}{D_2}\right)^2$$

In the formula, exponents were selected to reflect acceleration varying as the square root of kinetic energy in turn varying as weight of high explosive, and acceleration varying inversely as the area of an expanding circle.

To test the formula, Coast and Geodetic Survey results from a 26 July 1952 quarry shot at Corona, California, were inserted and a prediction made for the 5 April 1957, NTS underground 50-ton high-explosive shot.

$$a_2 = 0.13\left(\frac{50}{188}\right)^{1/2}\left(\frac{1290}{310}\right)^2 = 1.16 \text{ g}$$

Results actually recorded 310 feet from the 50-ton shot by Coast and Geodetic personnel were (see Appendix, Figure A.5 for tracing of record):

a_2 = 1.85 g (single-component maximum)

A_2 = 7.15 cm (single-component, single-amplitude, maximum transient ground displacement)

On the basis of these results and on the basis of the ratio of trace

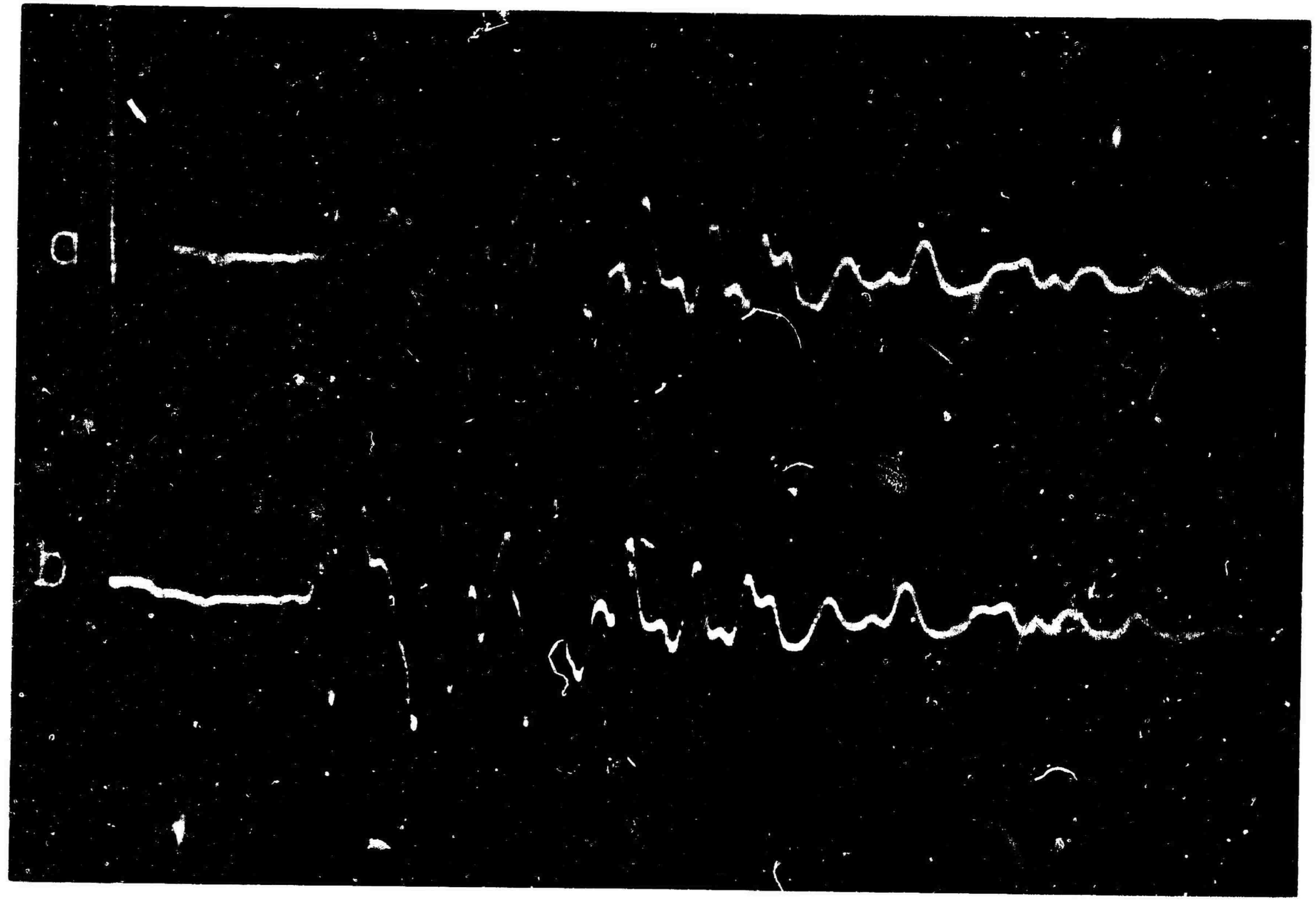


Fig. 2.2 Simulated response of an accelerometer to a previously recorded acceleration. The graphs indicate the reliability of a Coast and Geodetic Survey accelerometer by showing that the motion it recorded during Rainier was reproduced with a high degree of accuracy by an electric circuit equivalent to the accelerometer. a- Acceleration recorded by a C & GS accelerometer during Rainier. b- Response of simulated accelerometer to recorded acceleration shown in "a".

amplitudes recorded at the Eureka, Nevada, Coast and Geodetic Survey teleseismic station from the NTS 10-ton high explosive underground shot on 21 February 1957 and the 50-ton shot on 5 April 1957, the formula was revised to:

$$a = 1.85 \left(\frac{W}{50}\right)^{3/4} \left(\frac{310}{D}\right)^{2} \qquad (2.1)$$

In addition, on the theory that surface motion was approximately simple harmonic, a similar formula was set up for transient displacements:

$$A_2 = 7.15 \left(\frac{W}{50}\right)^{3/4} \left(\frac{310}{D}\right)^{2} \qquad (2.2)$$

Formulas (2.1) and (2.2) were used as guides in adjusting seismometer constants to the final values shown in Table 2.1. Construction of the instruments in some cases prevented fitting constants to optimum values set by the formulas.

TABLE 2.1 STRONG-MOTION SEISMOMETER CONSTANTS

Station	Seismometer No. Accelerometer	Seismometer No. Disp. meter	Pendulum disp. for trace up on record*	Period	Damping ratio†	Sensitivity	Static or lever magnification
				sec		cm/g	
01	Z 1007		Up	0.149	10	61.2	111
	R 1008		Away	0.149	10	63.2	115
	T 1009		Left	0.147	13	61.0	113
		Z 11	Down	2.04	10		2.9
		R 51	Away	2.24	10		5.6
		T 50	Right	2.03	10		5.0
02	1010		Up	0.170	10	79.9	111
	1011		Away	0.170	8	82.3	115
	1012		Left	0.176	11	87.5	114
		13	Down	1.95	10		2.3
		45	Away	2.93	10		5.7
		44	Right	3.67	10		5.5
03	345		Up	0.0898	6	21.7	108
	346		Away	0.0909	8	23.0	112
	347		Left	0.0882	7	22.0	114
		4	Down	2.30	10		3.1
		17	Away	3.20	10		3.4
		16	Right	2.68	10		3.3
04	1013		Up	0.0859	8	20.3	111
	1014		Away	0.0900	8	23.0	115
	1015		Left	0.0888	8	22.4	115
		6	Down	1.92	10		0.9
		35	Away	3.32	10		1.0
		34	Right	3.08	10		1.0
05	1019		Up	0.0333	8	2.94	107
	1020		Away	0.0347	9	3.37	113
	1021		Left	0.0321	8	2.81	110
		7	Down	2.70	10		0.9
		41	Away	2.99	10		0.9
		40	Right	3.21	10		0.9
06	1025		Up	0.0294	11	2.38	111
	1026		Away	0.0288	9	3.18	115
	1027		Left	0.0284	8	2.21	112
		9	Down	2.05	10		0.5
		37	Toward	2.43	10		0.5
		36	Left	2.28	10		0.5
07	1022		Up	0.0354	9	3.39	109
	1023		Away	0.0344	8	3.37	115
	1024		Left	0.0352	10	3.38	110
		8	Down	1.80	10		0.6
		43	Away	3.13	10		0.9
		42	Right	3.06	10		1.0
08	354		Up	0.0281	8	2.20	112
	355		Away	0.0290	8	2.37	114
	356		Left	0.0288	6	2.34	114
		10	Down	1.85	10		0.6
		39	Toward	2.35	10		0.5
		38	Left	2.50	10		0.5
09	1016		Up	0.0848	10	19.4	109
	1017		Away	0.0853	12	18.7	104
	1018		Left	0.0860	7	21.7	118
		5	Down	1.68	10		3.4
		19	Away	3.04	10		3.4
		18	Right	2.87	10		3.4
7.2a2 North		BJM 1	Up	1.25	10		140
		VM 7	Away	3.0	10		124
		VM 8	Left	3.0	10		126
Wood-Anderson Seismographs at Seven Offsite Stations§			?	0.?	near critical		2800

* Convention - Facing zero along radial line.

† Damping ratios for accelerometers accurately scaled from test grams.
Damping ratios for displacement meters measured visually - accuracy ± 2.

§ Constants are those reported by Seismological Laboratory, Pasadena, and University of California.

CHAPTER 3

RESULTS

3.1 STRONG MOTION

Readable seismograms of Rainier were obtained from the ten on-site Coast and Geodetic Survey strong-motion seismographs. (Partial tracings are shown in Figures 3.1 and 3.2.) Accelerometers used on the project measured accelerations only for ground periods substantially larger than instrumental periods. Some of the highest accelerations as recorded were associated with sharp, high-frequency impulses - in evaluating these, ground period as well as trace amplitude was considered. Lower frequency waves were measured directly from trace amplitudes and are considered reliable within 10 or 15 per cent. Ground displacement periods in all cases were considerably less than instrumental periods, thus meeting the criterion of trace amplitude being proportional to displacement. Displacement results are considered reliable within 10 or 15 per cent, except for several cases where the zero positions of instrument booms were permanently shifted by high accelerations.

Acceleration data are summarized in Table 3.1 and displacement data in Table 3.2. Remarks in the summaries such as "sharp spike" or "poor record" indicate components for which estimated reliability might be less than 85 to 90 per cent.

As maximum acceleration attenuated to 0.13 g at 4,390 feet, the radius within which damage might have occurred appears limited to about 1 mile. Very few of the observers stationed 2-1/2 miles from the shot reported having felt any ground motion.

From an engineering standpoint, maximum acceleration alone is not a reliable criterion of structural damage. Relative maximum velocity response of single degree of freedom oscillators to an acceleration function offers a better approach. (See Reference 2.) Utilizing the electric Analog-type Response Spectrum Analyzer system at the California Institute of Technology

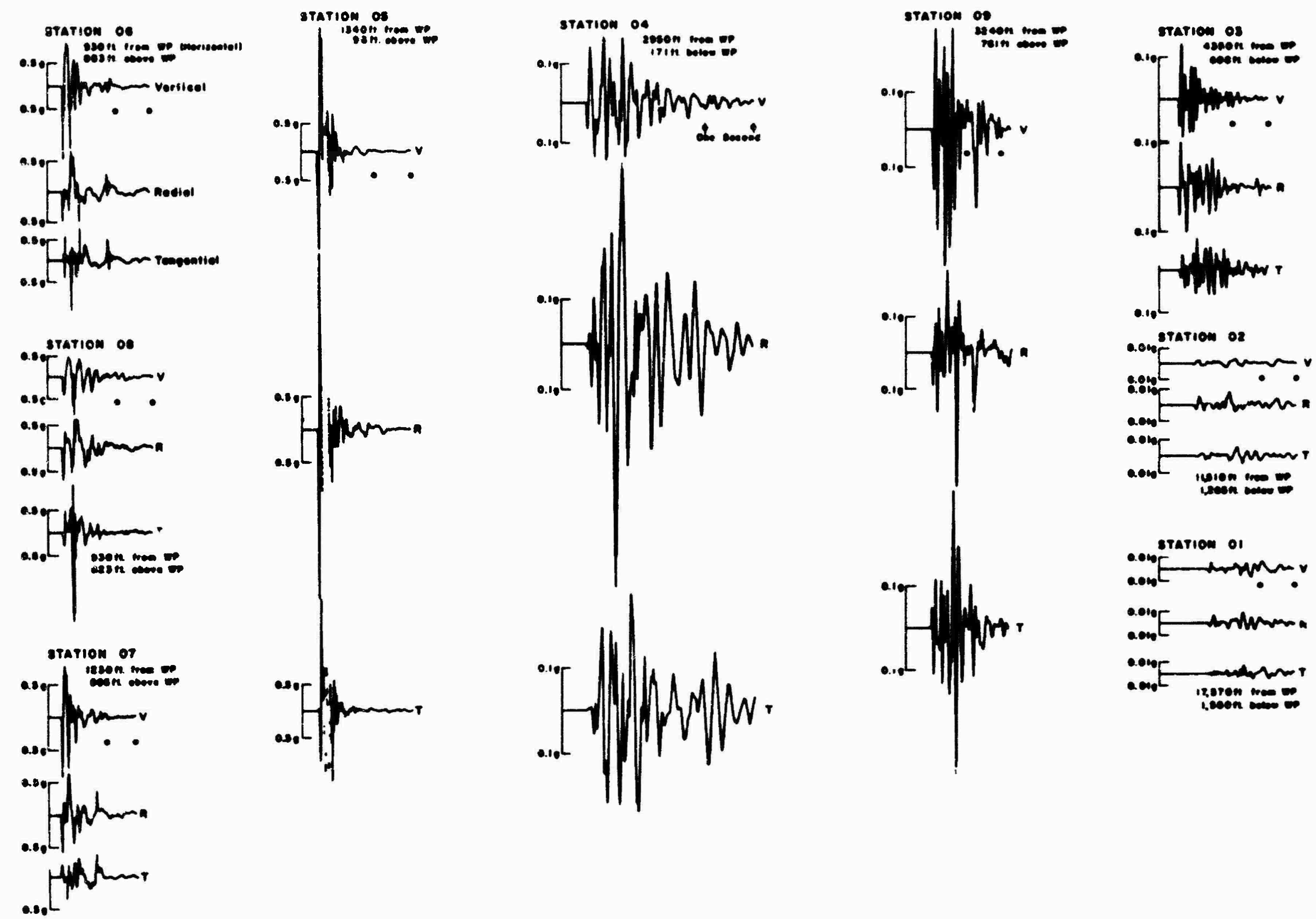


Fig. 3.1 Tracings of acceleration records. Only the larger amplitude portions of the records at each station are shown, together with enough data for rough quantitative interpretation. Trace amplitudes above the rest position represent pendulum motion vertically upward, radially away from zero or WP (working point), and tangentially to left when facing zero.

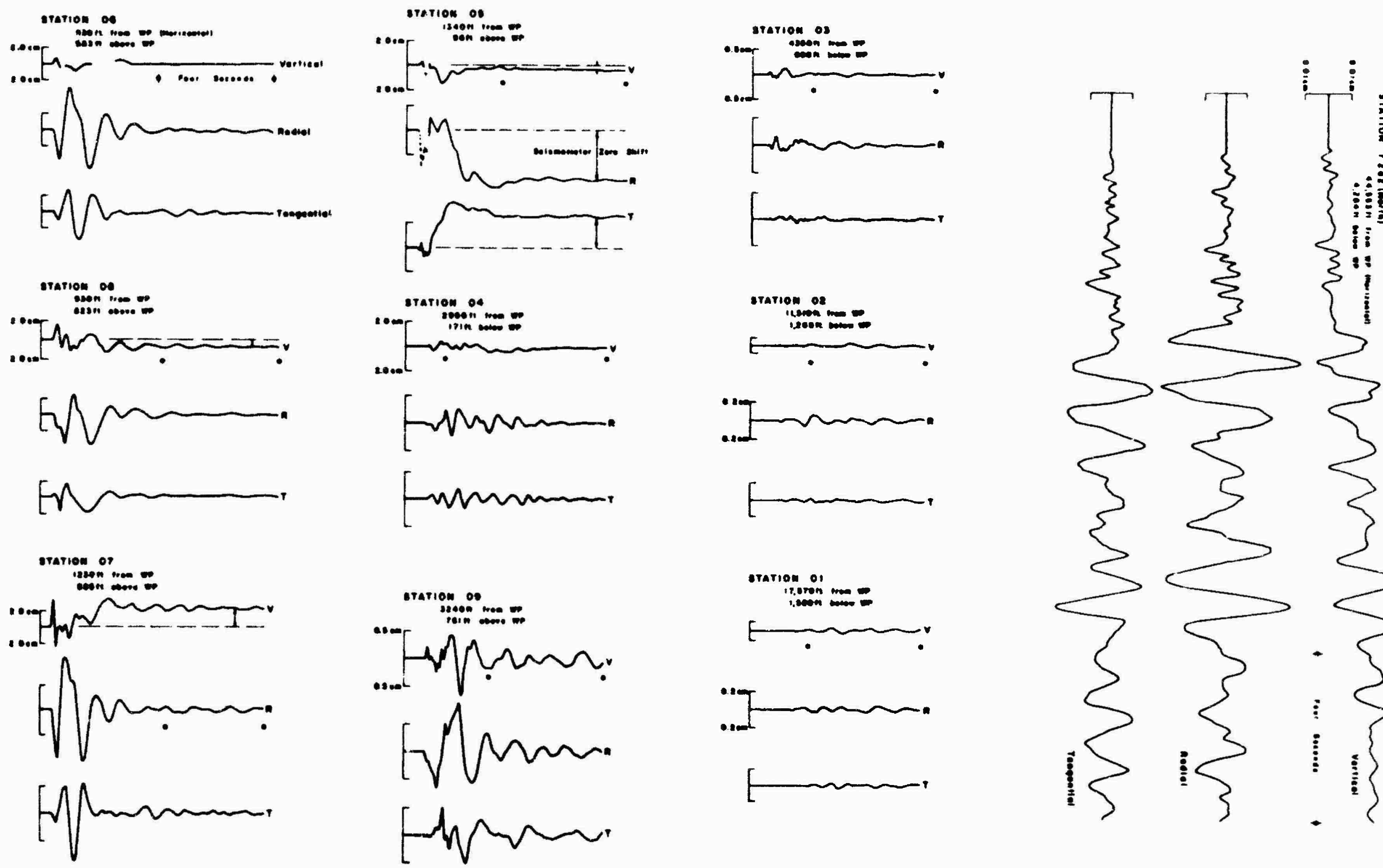


Fig. 3.2 Tracings of deplacement records. Only the larger amplitude portions of the records at each station are shown, together with enough data for rough quantitative interpretation. Trace amplitudes above the rest position represent pendulum motion vertically downward, radially away from zero or WP (Working Point), and tangentially to right when facing zero.

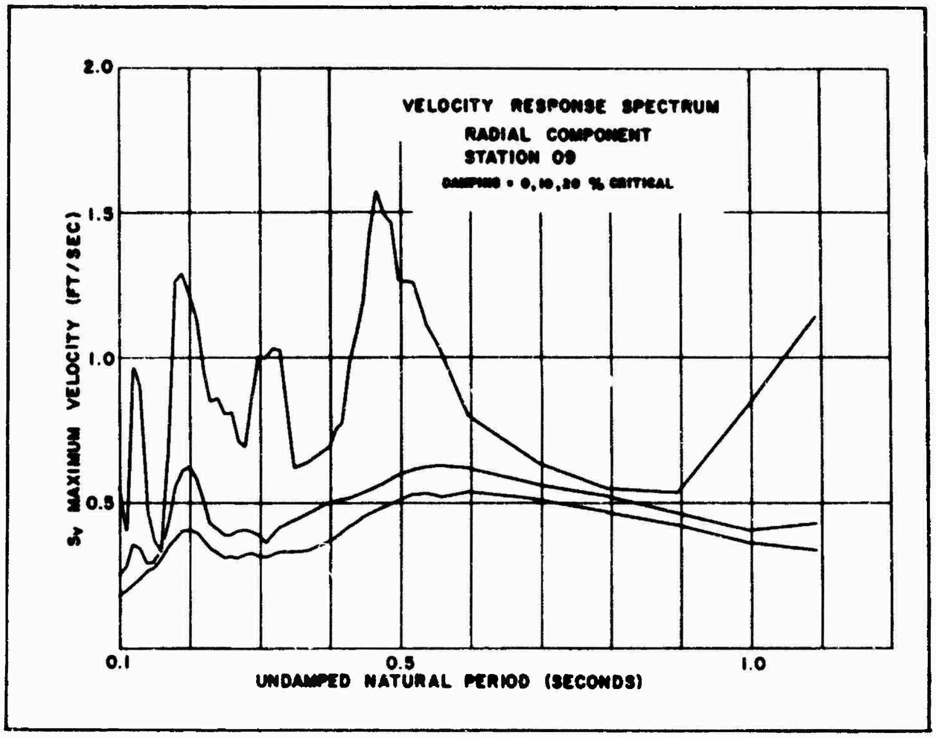
TABLE 3.1 FIRST MOTION AND MAXIMUM ACCELERATION DATA

Station No., distance, and foundation	Component	Period	Acceleration	Time after first arrival	Remarks
		sec	g	sec	
6003.01	Z	0.1	0.004	0	Up
17569 ft (horiz.)		0.2	0.008	1.0	
17640 ft (slant)	R	0.1	0.004	0	Away
Quartzite		0.2	0.009	1.04	
Cross-over station	T	0.1	0.003	0	Right
with Geological		0.1	0.007	1.03	
Survey					
6003.02	Z	0.1	0.002	0	Up
11508 ft		0.5	0.005	1.21	
11580	R	0.2	0.003	0	Away
Dolomite		0.3	0.008	1.03	
	T	0.2	0.001	0	Left
		0.3	0.005	1.25	
6003.03	Z	0.1	0.07	0	Up
4348 ft		0.1	0.13		
4390 ft	R	0.1	0.06	0	Away
Bedded tuff		0.2	0.10	0.17	
	T	0.09	0.016	0	Left
		.15	0.07	.48	
6003.04	Z	0.2	0.07	0	Up
2948 ft		0.25	0.19	0.8	
2950 ft	R	0.08	0.01	0	Away
Bedded tuff		0.2	0.54	0.8	
	T		0.002	0	Right
		0.3	0.27	0.9	
6003.05	Z	0.03	0.94	0	Up
1338 ft		0.07	2.2	0.1	May be 1.4 g or one spike
1340 ft	R	0.1	2.6	0	Away. May be as high as 3 g
Bedded tuff	T		0.03	0	Right
Tunnel station		0.01-0.1	1.3	0.3	One spike may be 2.0 g or higher. Traces on this record were seriously overlapped.
Cross-over with Sandia Corp.					
6003.06	Z	0.1	1.6	0	Up. Cross-over station
932 ft	R	0.06	0.5	0	Away. with Stanford
1280 ft		0.05	0.65	0.3	Research Corp.
Welded tuff	T	0.02	0.14	0	Right
on mesa		0.02	2.6	1	Sharp spike
6003.07	Z	0.1	0.91	0	Up. Cross-over station
1230 ft	R	0.1	0.59	0	Away. with Stanford
1516 ft		0.3	0.62	0.62	Research Corp.
Welded tuff	T	0.1	0.19	0	Right. Record from this
on mesa		0.07	0.41	0.2	station very similar to station 06 record.
6003.08	Z	0.2	0.42	0	Up
932 ft		0.02-.06	0.90	0.25	
1242 ft	R	0.1	0.69	0	Away
Welded tuff	T	0.25	0.4	0	Left
on mesa		0.03	2.0	0.25	
6003.09	Z	0.1	0.16	0	Up
3240 ft		0.1	0.36	0.4	
3329 ft	R	0.1	0.09	0	Away
Welded tuff		0.1	0.34	0.7	
on mesa	T		0.11	0	Right
		0.2	0.34		

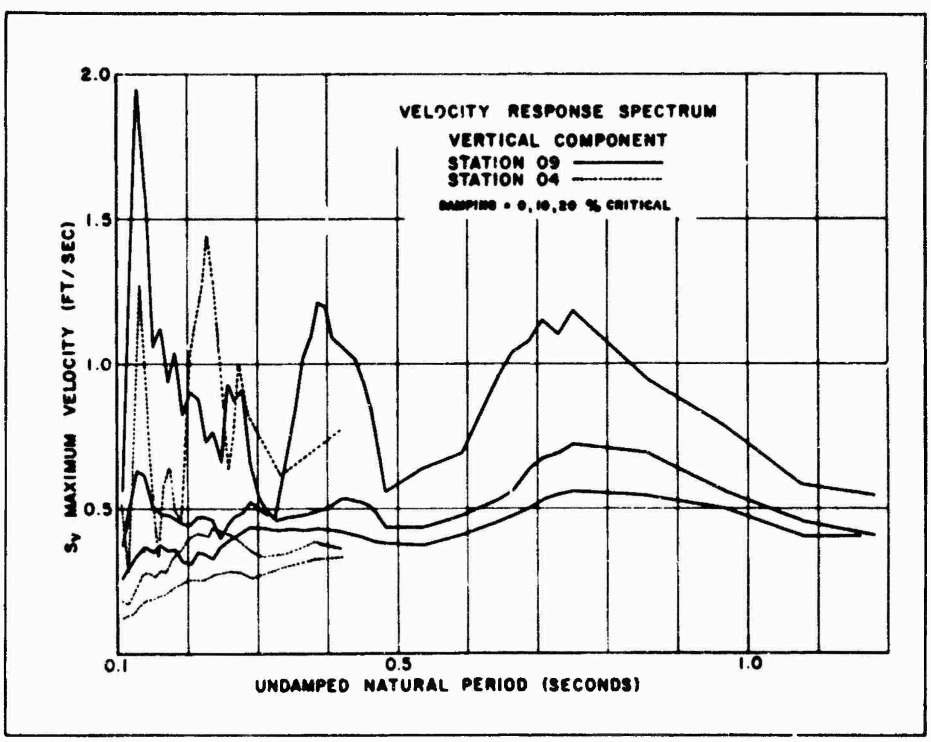
TABLE 3.2 MAXIMUM DISPLACEMENT DATA

Station No., distance, and foundation	Component	Maximum Displacement Period	Maximum Displacement Amplitude	Remarks	
		sec	cm		
6003.01	Z	0.7	0.045	Cross-over station with	
17569 ft (horiz.)				Geological Survey	
17640 ft (slant)	R	0.7	0.030		
Quartzite	T	0.5	0.040		
6003.02	Z	1.0	0.043		
11508 ft					
11580	R	0.8	0.061		
Dolomite	T	0.4	0.022		
6003.03	Z	0.7	0.14		
4348 ft					
4390 ft	R	0.3	0.15		
Bedded tuff			0.06		
6003.04	Z	0.4	0.34		
2948 ft					
2950 ft	R	0.3	0.84		
Bedded tuff	T	0.4	0.60		
6003.05	Z		1.28	Poor record	Tunnel station
1338 ft					Cross-over with
1340 ft	R		3.73	Poor record	Sandia Corp.
Bedded tuff	T		3.16	Poor record	
6003.06	Z		0.90	Poor record	Cross-over
932 ft					station with
1280 ft	R	1.3	5.40		Stanford Research
Welded tuff	T	.9	3.64		Corp.
6003.07	Z	1.0	3.01	Poor record	Cross-over
1230 ft					station with
1516 ft	R	1.1	3.46		Stanford
Welded tuff	T	.9	3.10		Research Corp.
6003.08	Z	.3	1.41	Poor record	
932 ft					
1242 ft	R	1.2	3.90		
Welded tuff	T	1.9	1.96		
6003.09	Z	.7	0.70		
3240 ft					
3329 ft	R	1.5	0.85		
Welded tuff	T	.9	0.52		
7.2a2 (North)	Z	1.2	0.014		
44,553 (horiz.)	R	1.3	0.037		
Deep alluvium	T	1.3	0.025		

Earthquake Research Laboratory, several Rainier strong-motion records were subjected to such an analysis. The results are shown in Figure 3.3. For comparison, the velocity spectrum from an accelogram that was recorded about 7 miles from the epicenter of the 22 March 1957, magnitude 5.3, San Francisco earthquake is shown in Fig. 3.4. Points on the curves give a relative measure of maximum kinetic energy that would have been attained during the time of ground motion by simple structures of various periods and damping. To illustrate, a structure with 0.5-second period and 10 per

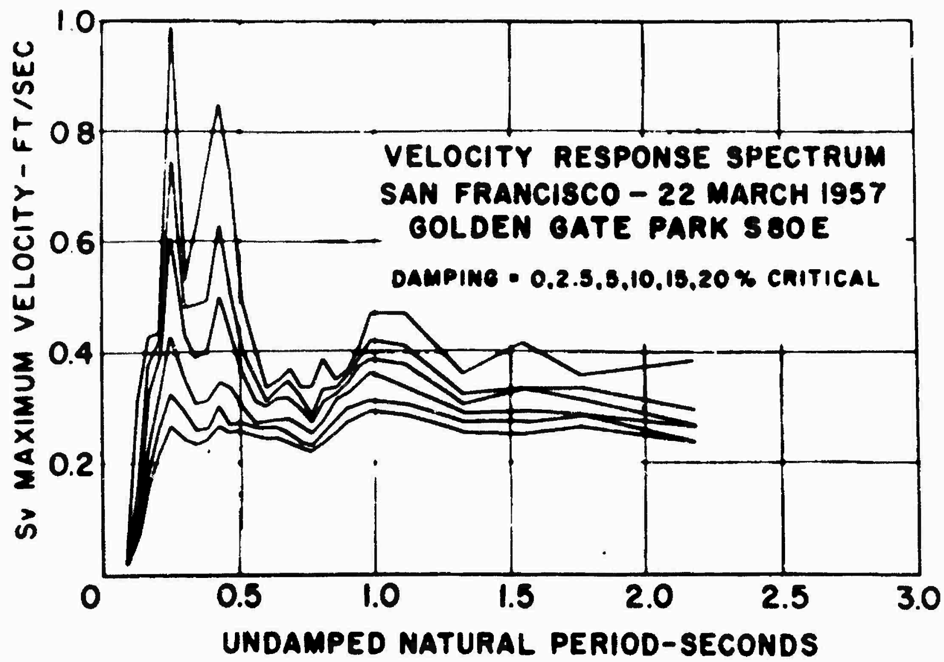


Graph A

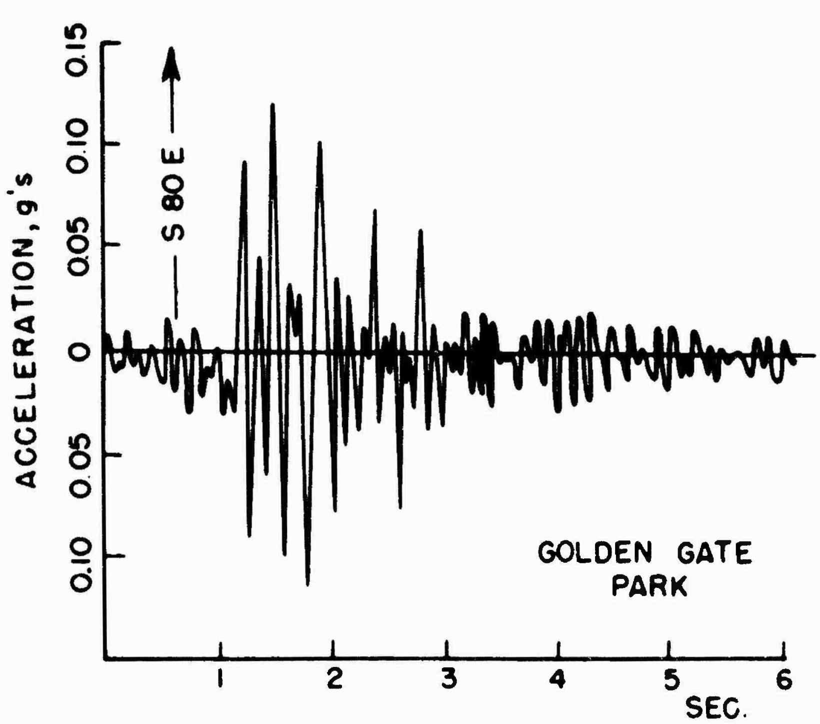


Graph B

Fig. 3. 3 Relative maximum velocity response spectrums. Graphs A and B show the maximum response of single degree of freedom oscillators to acceleration recorded at two C & GS stations in the direction indicated.



Graph C



Graph D

Fig. 3.4 Relative maximum velocity response spectrum. Graph C shows the maximum response of single degree of freedom oscillators to earthquake acceleration shown in graph D.

cent critical damping at Rainier Station 09 would have attained roughly $(0.6/0.3)^2$ or 4 times the kinetic energy of the same structure located at Golden Gate Park. The comparison is for one direction of horizontal motion.

3.2 RECORDED vs PREDICTED GROUND MOTION

In Tables 3.3 and 3.4 the maximum accelerations and displacements recorded by the ten on-site strong-motion seismographs and maxima recorded by seven off-site Wood-Anderson seismographs are compared with values predicted by the empirical formulas given in Chapter 2, Section 2.3, of this report. As further illustration, graphical comparison of the same data is given in Figures 3.5, 3.6, 3.7, and 3.8.

Predictions within the ratio limits established by Rainier data were also made for two unrelated underground explosions:

(a) South Holston Dam, Tenn., 5 February 1949, 1,362,985 lb of high explosive. (See Reference 3.)

	Maximum displacement		Formula	Ratio recorded
Distance	Period	Amplitude	prediction	to predicted
ft	sec	cm	cm	
8,000	0.33	0.068	0.128	0.53
11,500	0.33	0.046	0.062	0.74
38,500*	0.30*	0.018*	0.0033*	0.18*

* From an internal Coast and Geodetic Survey report by D. S. Carder.

(b) Corona Quarry, California, 18 February 1958, 1,347,000 lb of high explosive. (Recorded by Coast and Geodetic Survey.)

	Maximum acceleration		Ratio of recorded
Distance	Recorded	Predicted	to predicted
ft	g	g	
1,200*	0.23	0.87	0.26
1,700†	0.31	0.43	0.72

* On floor slab of heavy mill building.

† On natural ground.

TABLE 3.3 COMPARISON OF RECORDED AND PREDICTED MAXIMUM SINGLE COMPONENT ACCELERATIONS

Station	Distance to source		Maximum acceleration (gravity) recorded			Predicted	Ratio of recorded to predicted
			Z	R	T		
	ft	km					
01	17,640		0.008	0.009	0.007	0.008	1.1
02	11,580		0.005	0.008	0.005	0.019	0.42
03	4,390		0.13	0.10	0.07	0.130	1.0
04	2,950		0.19	0.54	0.27	0.288	1.8
05	1,340		2.2	2.6	1.3	1.39	1.8
06	1,280		1.6	0.65	2.6	1.53	1.7
07	1,51[illegible]		0.91	0.62	0.41	1.9	0.83
08	1,242		0.90	0.69	2.0	1.62	1.2
09	3,329		0.36	0.34	0.34	.226	1.6
7.2a2 N*	44,553	13.6	0.00039	0.00088	0.00060	0.0013	0.68
Tinemaha*		180.7	East-West		0.000016	0.0000071	2.2
Hoover Dam*		185.4	East-West		0.0000046	0.0000068	0.34
Pasadena*		382.2	East-West		0.00000031	0.0000016	0.19
Mount Hamilton*		482.8	?		0.0000014	0.0000010	1.4
Palo Alto*		530.4	North-South		0.00000042	0.00000083	0.50
Berkeley*		540.5	East-West		0.00000020	0.00000080	0.25
San Francisco*		556.5	East-West		0.00000026	0.00000075	0.35

* Acceleration was computed from displacement by simple harmonic motion formula $a = \frac{4\pi^2 A}{T_e^2}$.

TABLE 3.4 COMPARISON OF RECORDED AND PREDICTED MAXIMUM SINGLE COMPONENT TRANSIENT DISPLACEMENTS

Station	Distance to source		Maximum displacement (cm) recorded			Predicted	Ratio of recorded to predicted
			Z	R	T		
	ft	km					
01	17,640		0.045	0.030	0.040	0.031	1.45
02	11,580		0.043	0.061	0.022	0.072	0.85
03	4,390		0.14	0.15		0.50	0.30
04	2,950		0.34	0.84	0.60	1.11	0.76
05	1,340		1.28	3.73	3.16	5.39	0.69
06	1,280		0.90	5.40	3.64	5.90	0.91
07	1,516		3.01	3.46	3.10	4.21	0.82
08	1,242		1.41	3.90	1.96	6.72	0.57
09	3,329		0.70	0.85	0.52	0.87	0.98
7.2a2 (North)	44,553	13.6	0.014	0.037	0.025	0.0049	7.6
Tinemaha		180.7	East-West		0.00025	0.000028	8.9
Hoover Dam		185.4	East-West		0.00011	0.000026	2.17
Pasadena		382.2	East-West		0.0000094	0.0000061	1.54
Mount Hamilton		482.8	?		0.000034	0.0000038	8.9
Palo Alto		530.4	North-South		0.000015	0.0000032	4.7
Berkeley		540.5	East-West		0.0000059	0.0000031	1.9
San Francisco		556.5	East-West		0.0000094	0.0000029	3.2

Predictions were probably closer than indicated for these quarry shots, as the total amount of high explosive was not fired instantaneously. Had the largest amount of explosive in single delay been used in the formulas instead of the total amount, the predicted values would have been lower, and, thus, closer to the recorded values.

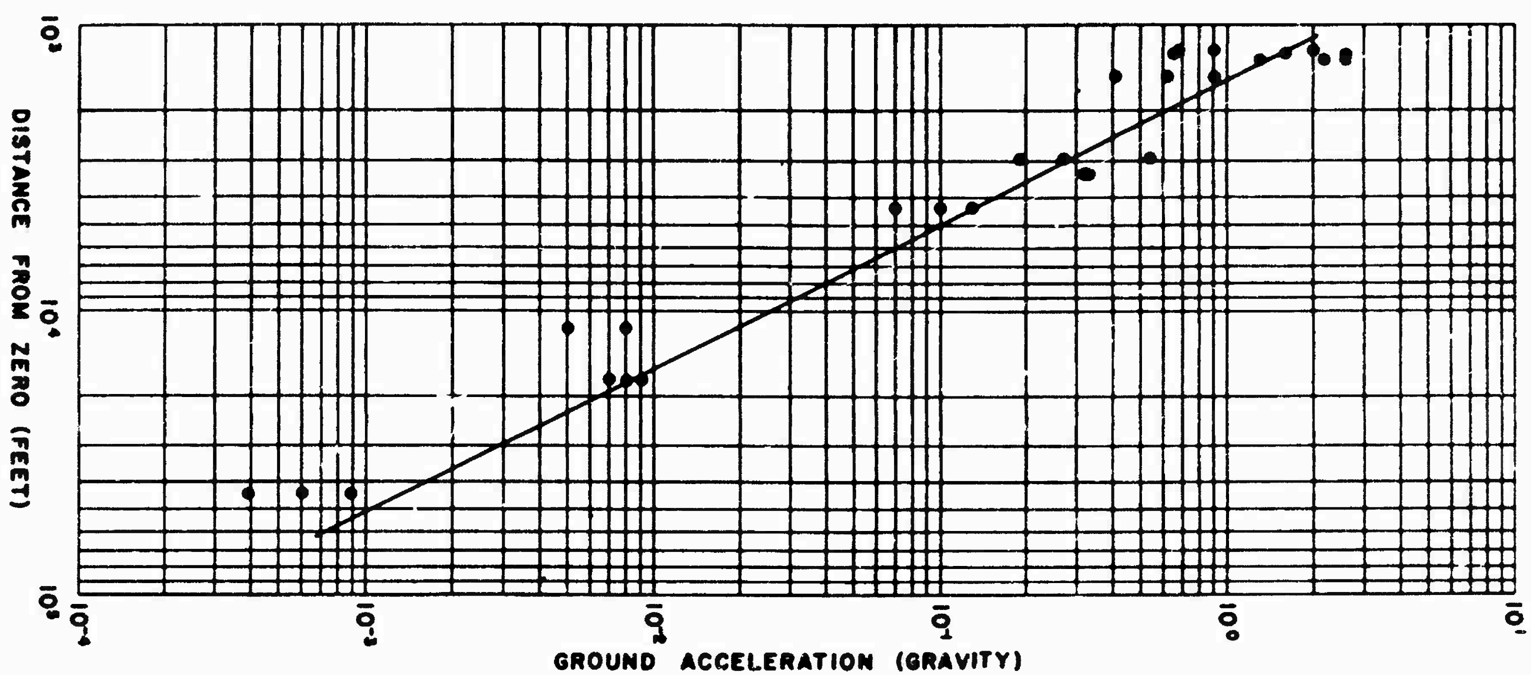


Fig. 3.5 Predicted and recorded accelerations. The closest station to zero for which data are plotted is 08 at 1242 ft; the farthest is 7.2a2 N at 44, 553 ft.

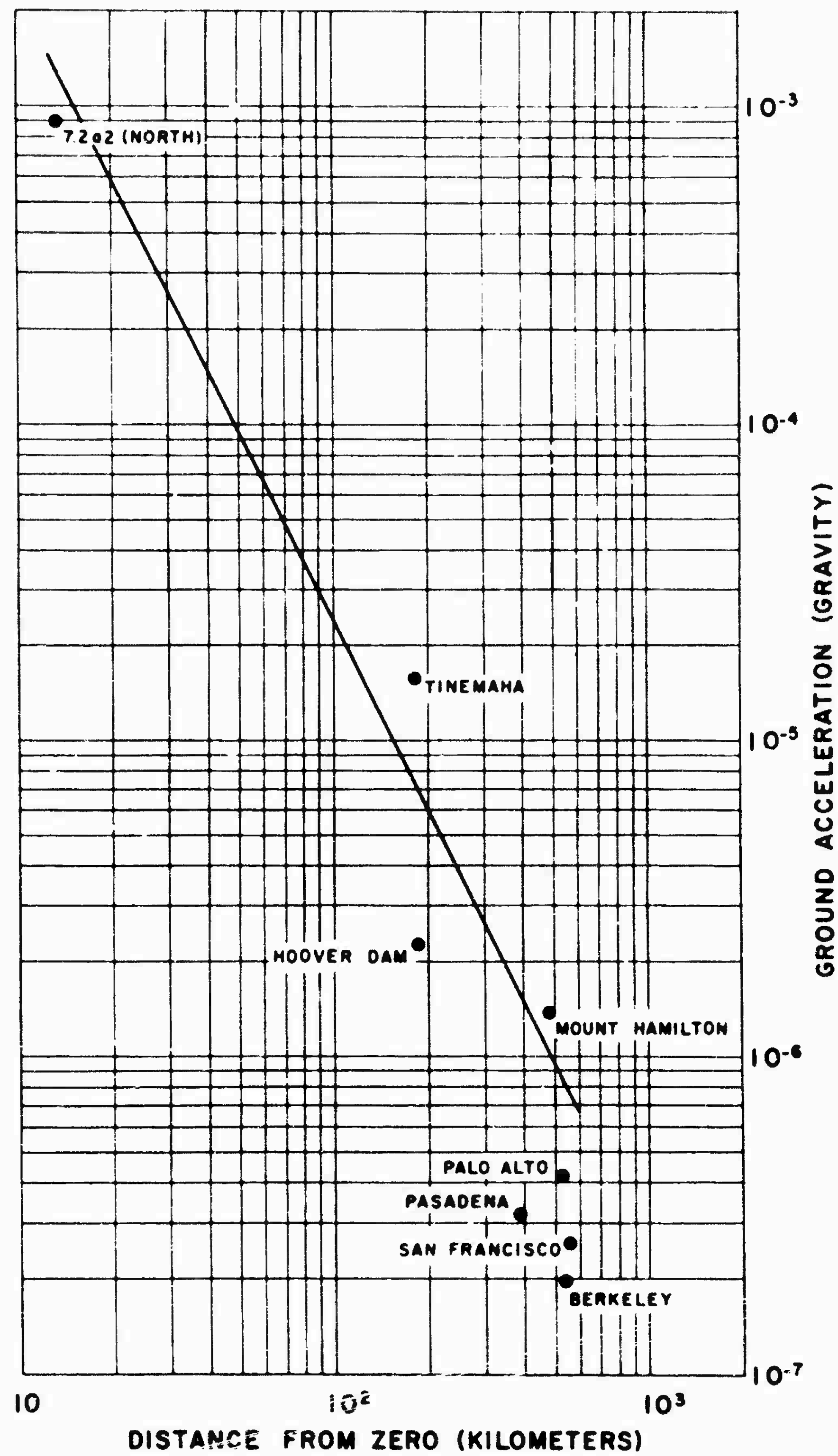


Fig. 3.6 Predicted and recorded accelerations. The closest station to zero for which data are plotted is 7.2a2 N at 13.6 km; the farthest is San Francisco at 556 km.

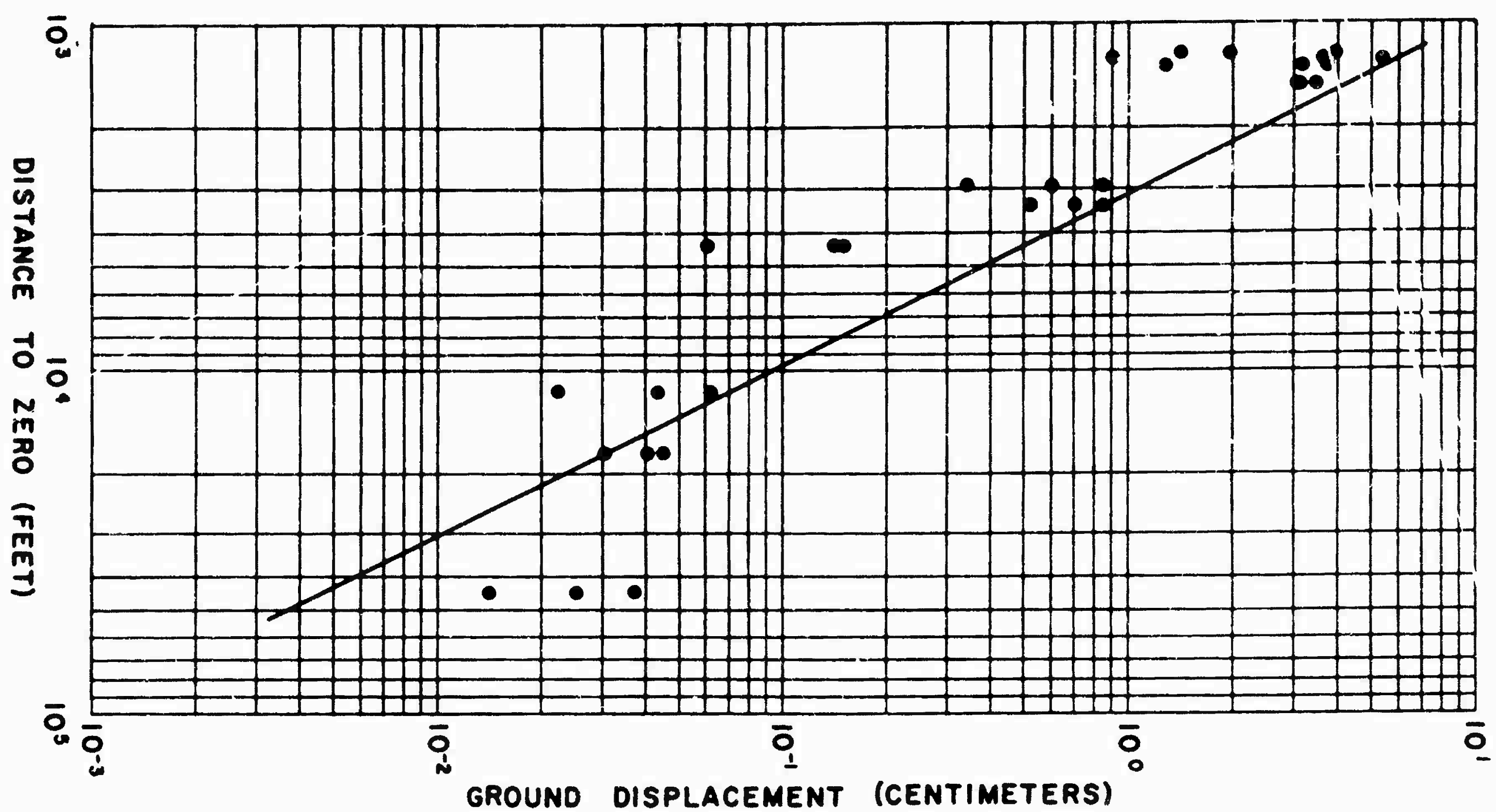


Fig. 3.7 Predicted and recorded displacements. The closest station to zero for which data are plotted is 08 at 1242 ft; the farthest is 7.2a2 N at **44**, 553 ft.

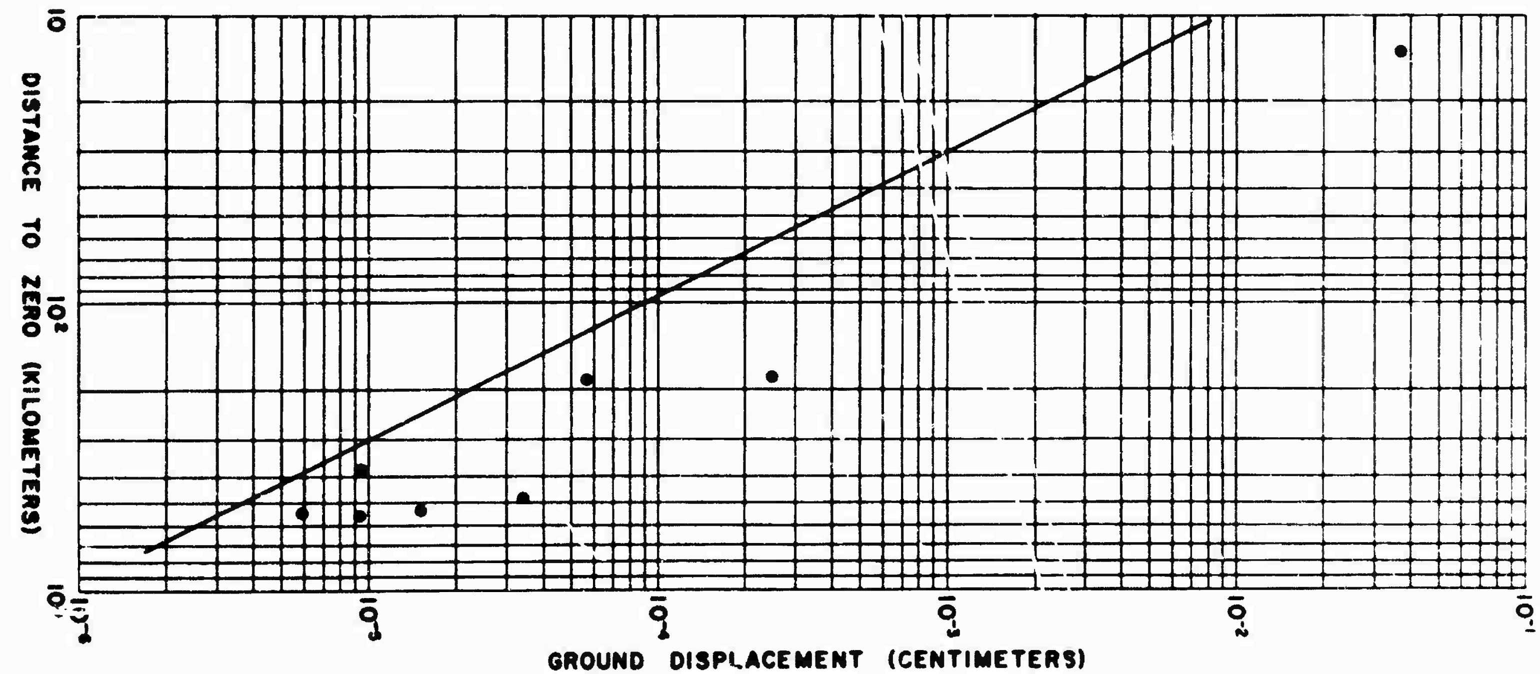


Fig. 3.8 Predicted and recorded displacements. The closest station to zero for which data are plotted is 7.2a2 N at 13.6 km; the farthest is San Francisco at 556 km.

3.3 WOOD-ANDERSON SEISMOGRAPH

In addition to using the seven Wood-Anderson seismograph records borrowed from off-site stations to extend strong-motion results, it was of interest to use them for calculating so-called earthquake magnitude of Rainier. The term magnitude as developed by Dr. C. F. Richter and Dr. Beno Gutenberg for earthquakes is defined as: "The logarithm of the maximum trace amplitude expressed in thousandths of a millimeter with which the standard short-period torsion seismometer (Wood-Anderson, free period 0.8 second, static magnification 2800, damping nearly critical) would register that earthquake at an epicentral distance of 100 kilometers."

Utilizing Gutenberg-Richter methods, tables and formulas (Reference 4) the following results were obtained for magnitude (M) of Rainier:

Tinemaha	M = 4.8	Palo Alto	M = 4.6
Hoover Dam	M = 5.0	Berkeley	M = 4.2
Pasadena	M = 4.0	San Francisco	M = 4.6
Mount Hamilton	M = 5.0	Average	M = 4.6

At present Gutenberg-Richter suggest the following formula relating magnitude of earthquakes to energy

$$\text{Log } E = 9.4 + 2.14\ M - 0.054\ M^2$$

For a magnitude 4.6 earthquake the formula gives $E = 10^{18.1}$ ergs, where E is the total energy radiated in elastic waves. However, the fact that earthquakes of this magnitude are felt up to 60 miles from epicenter while Rainier was scarcely felt at 2-1/2 miles suggests caution in using magnitude-energy formulas to draw conclusions regarding underground explosions.

3.4 TELESEISMIC

Teleseismic data used in maximum amplitude attenuation are discussed in detail in Section 4. Discussion here will be limited to the ability of teleseismic stations to record the initial or P-waves. Benioff short period seismographs were used almost exclusively to record P-wave data at distances beyond 180 km. Sprengnether data from Fresno and Reno are exceptions.

Records from stations out to about 730 km were not very different in character or amplitude from other records of the larger Nevada explosions. At Laramie, approx. 1000 km, the seismogram assumed the character of a distant teleseism with a fairly sharp initial P, estimated amplitude about 5 mμ, and a train of weak S or surface waves having about the same amplitude. At Fayetteville, 1970 km, an assumed initial P is very weak, which is accepted with reservations only because it checked with records of other

Nevada explosions. Its amplitude was somewhat smaller than 1 $m\mu$.

Travel time data are given in a separate report by Bailey and Romney.

Geophysical parties using exploration seismic equipment claim to have recorded the Rainier explosion at various distances. These include a University of Wisconsin party operating in Mexico at estimated distances of 1800 to 2200 km, and sharp P and S waves were recorded by a seismic level recorder using a 2-cps pickup at the University of Michigan, Ann Arbor. At Toronto, a long-period Willmore seismograph recorded a wave that may have been associated with the Rainier shot. Many other alleged recordings in the United States and elsewhere may have resulted from an earthquake.

CHAPTER 4

ENERGY RELATIONSHIPS, GROUND DISPLACEMENTS, AND SOURCE ENERGY

4.1 INTRODUCTION

An earthquake or an explosion on or within the earth generates elastic waves that pass through the rock according to certain laws. These waves contain a certain amount of energy which can be measured in part as they pass a seismograph station located either on or within the earth. If the energy contained in the wave as it passes a seismograph station is known, the energy that enters the ground in the form of seismic waves at the source may be estimated if the wave paths and absorption and boundary losses enroute are known. Therein lies the uncertainty in estimating seismic energy at the source, and this uncertainty constitutes a part of our problem.

4.2 ENERGY RELATIONSHIPS

4.2.1 Symbols

E	Total seismic energy at the source.
E_s	Energy per cm^2 in wave front passing station.
M	Mass per unit cross section of rock column under distortion in the wave front.
ω	Particle velocity.
λ	Wave length.
A_h	Amplitude (rest-to-peak) of particle within rock mass.
A	Amplitude of particle at the surface.
v	Speed of wave front.
ρ	Density of medium through which elastic wave is propagated.
t	Time duration of pulse being measured.
r	Ratio of total E_s to energy in the pulse being measured.

T Period of the wave being measured.

R Distance, station to source.

k An absorption factor.

Q A loss by refraction factor--ratio of energy in wave front as it leaves the source to that which reaches as far as the station--assuming horizontal homogeneity and neglecting absorption.

All units are cgs, except that R, when convenient, is in kilometers. Subscripts o, 1, 2, apply to particular cases.

4.2.2 Equations

Energy per unit wave front because of a seismic wave passing a point in the rock is based on the familiar kinetic energy equation

$$E_s = \frac{1}{2} M\omega^2$$

Actually the average kinetic energy is half of this but as kinetic energy falls, potential energy increases by a like amount. From the relations $\omega = 2\pi A_h/T$ and $M = \rho\lambda = \rho v T$, the energy formula becomes

$$E_{sw} = 2\pi^2 \rho v A_h^2/T \quad \text{for a single wave or}$$

$$E_s = 2\pi^2 \rho \Sigma v A_h^2/T$$

for all waves passing the point. If a single pulse on a seismogram is measured and if equal amplitudes and periods of the waves in the pulse are assumed, the formula is simplified to

$$E_s = 2\pi^2 \rho v r t A_h^2/T^2$$

If the recording station is on the surface, as it usually is, the emergent wave usually has twice the amplitude of a wave confined underground. The energy formula measured from a pulse on the seismogram thus becomes

$$E_s = \frac{\pi^2}{2} \frac{\rho v r t A^2}{T^2} \tag{4.1}$$

or

$$E_s = \frac{\pi^2}{2} \rho v \Sigma \frac{A^2}{T} \quad \text{if all waves are measured.}$$

The total seismic energy leaving the source is measured from the volume of the wave front assuming that it left the source unimpeded, multiplied by the ratio of the loss enroute. This may be represented by

$$E = E_s Q S e^{k_1 R} \quad \text{where } S \text{ is the area of the wave front.}$$

If hemispherical wave fronts are assumed, $S = 2\pi R^2$. If measured energy

is assumed to be contained in body waves trapped in a surface layer of thickness h, $S = 2\pi Rh$. In empirical formulas, an exponential base 10 is more convenient to use. Therefore, if $k = 0.434k_1$,

$$E = 2\pi E_s QR^2 10^{kR} \tag{4.2}$$

if a hemispherical wave front is assumed; and

$$E = 2\pi E QRh 10^{kR} \tag{4.3}$$

if a cylindrical wave front is assumed.

These energy formulas were utilized by the senior author (Carder) in an attempt to evaluate seismic energies at the source of earlier nuclear explosions detonated on the Nevada and Pacific islands proving grounds. An absorption factor k was obtained from measurements of S-wave trains (believed confined to the surface layers) resulting from the Trinity explosion of July 1945. This explosion was recorded by a number of Benioff seismographs at distances ranging from 437 to 1050 km. Their magnifications were estimated from a direct comparison with Wood-Anderson responses and trace amplitudes from the Bikini Baker explosion. The waves under study were assumed confined to surface layering, their energy falling off linearly and exponentially, assuming absorption. From (4.3)

$$E = 2\pi E_{s1} QR_1 h 10^{kR_1} = 2\pi E_{s2} QR_2 h 10^{kR_2}$$

The assumptions of no refraction scatter and equal layer thickness between stations are made, therefore,

$$E_{s1} = E_{s2} R_2 / R_1 \times 10^{k(R_2 - R_1)}, \tag{4.4}$$

or from (4.1), assuming no change in density or seismic velocity between stations and by using corresponding wave trains on the records, it may be found that

$$k = \frac{\log \left(\dfrac{R_1 t_1 A_1^2 T_2^2}{R_2 t_2 A_2^2 T_1^2} \right)}{R_2 - R_1}$$

From the Trinity data, k was found to be about 0.0043 per km. Later a k of 0.005 per km seemed to give the better fit to most of the Nevada data and will be used in this discussion.

4.3 DERIVATION OF EMPIRICAL AMPLITUDE RELATIONSHIPS

Energy equations will be now applied to the Rainier problem. At distances of 180 km or greater, maximum amplitudes are in S or surface wave trains of about 20-sec duration, and the period of the individual waves is about 1 sec. Further, the energy in the S-surface group is considered only a part of the total. Consider it a third of the total, and if waves on only one component are measured, resultant energy is considered a ninth of the total. Near-the-source energy as measured from the seismogram represents the total, if all components are measured. Within 1500 feet of the source most of the seismic energy is confined to a pulse of 2 seconds duration and the component having the maximum amplitude contains from 4 to 5 tenths of the total. We will now use $k = 0.005$ per km, assume spherical wave fronts out to 100 km and cylindrical fronts beyond 100 km, and that $T_1 = T_2 = 1$ sec. We will use as a base a ground amplitude of 1.9×10^{-4} cm at a distance of 180 km, and refer to data from this base with zero subscripts. This is an approximate square root average between the Tinemaha and Hoover Dam Rainier amplitudes. From (4.4) and (4.1) and assuming $\rho = \rho_o$, $T = T_o$, and $v = v_o$ we have

$$\frac{E_s}{rt} \propto A^2 = \frac{r_o t_o}{rt} A_o^2 \frac{R_o}{R} 10^{k(R_o - R)}$$

or (4.5)

$$A^2 = \frac{K^2}{rtR} 10^{-kR}$$

Using $A_o = 1.9 \times 10^{-4}$ cm at 180 km and $k = 0.005$ per km, then $K = 0.1$, nearly. For R less than 100 km, using the above data,

$$A^2 = \frac{N^2}{rtR^2} 10^{-kR} \tag{4.6}$$

where $N = 1$ nearly and R is in kilometers.

If the period of the dominant wave measured is other than 1 sec, (4.5) and (4.6) become

$$A^2 = \frac{0.01\, T^2}{rtR} 10^{-kR} \tag{4.7}$$

for $T > 100$ km; and for $R < 100$ km,

$$A^2 = \frac{T^2}{rtR^2} 10^{-kR} \tag{4.8}$$

In Figure 4.1, the dashed branch of the curve neglects r and t, and the solid curve is a plot of Eqs. (4.5) and (4.6), using $r_o t_o = 180$ at 180 km and $rt = 6$ at 1 km, with gradation of rt prorated between 1 km and 180 km.

This solid curve from 3 to 100 km is constructed on the formula $(0.32/R) \times 10^{-0.006R}$ which includes the gradations in rt, with the gap from 100 to 180 km smoothed over.

The dotted line is the inverse square relationship represented by formula (2.2).

The small circles are the amplitude maxima measured from strong motion and teleseismic data. The small squares are South Holst n data from the table in Section 3.2a multiplied by 2, the yield factor of Eq. (2.2) inverted. The triangles are the measured or calculated displacement data from the 50-ton shot multiplied by 14.

4.4 DISCUSSION OF GROUND AMPLITUDE DATA

4.4.1 Rainier Data

The fit of field data from 1 km and beyond to the solid curve in Figure 4.1 is certainly not perfect, but is believed as satisfactory a fit as could be obtained from any other curve. One deviation is by a factor of 4; all others are well within a factor of 3. Doubtless slightly higher values for k would give more satisfactory results, and certainly, body waves near the source would be expected to have a different absorption factor than S-surface waves at some distance. Further refinements may result as more data are collected.

The Rainier data indicate an absorption factor in the rock of the mesa from distances of about 1200 feet out to about 2 miles. From Figure 4.1 suppose A at 0.3 km = 7 cm and 0.1 cm at 3 km. Using transmission of energy outward in the form of spherical waves, and assuming no change in periods, from the energy equations we have

$$k = \frac{\log\left(A_1^2 R_1^2 r_1 t_1 / A_2^2 R_2^2 r_2 t_2\right)}{R_2 - R_1} = 0.40 \text{ per km} \qquad (4.9)$$

The empirical formula (2.2), however, fits the close-in data--out to several kilometers--quite well, although (4.9) will be used in later energy calculations.

Special mention of displacement data at Station 7.2a2N, distance 13.6 km, is in order. The amplitude here is by a factor of 2.5 over the best empirical predictions and the duration of the wave train is probably 20 sec or more. This station is on deep alluvium. The results indicated here are therefore to be expected.

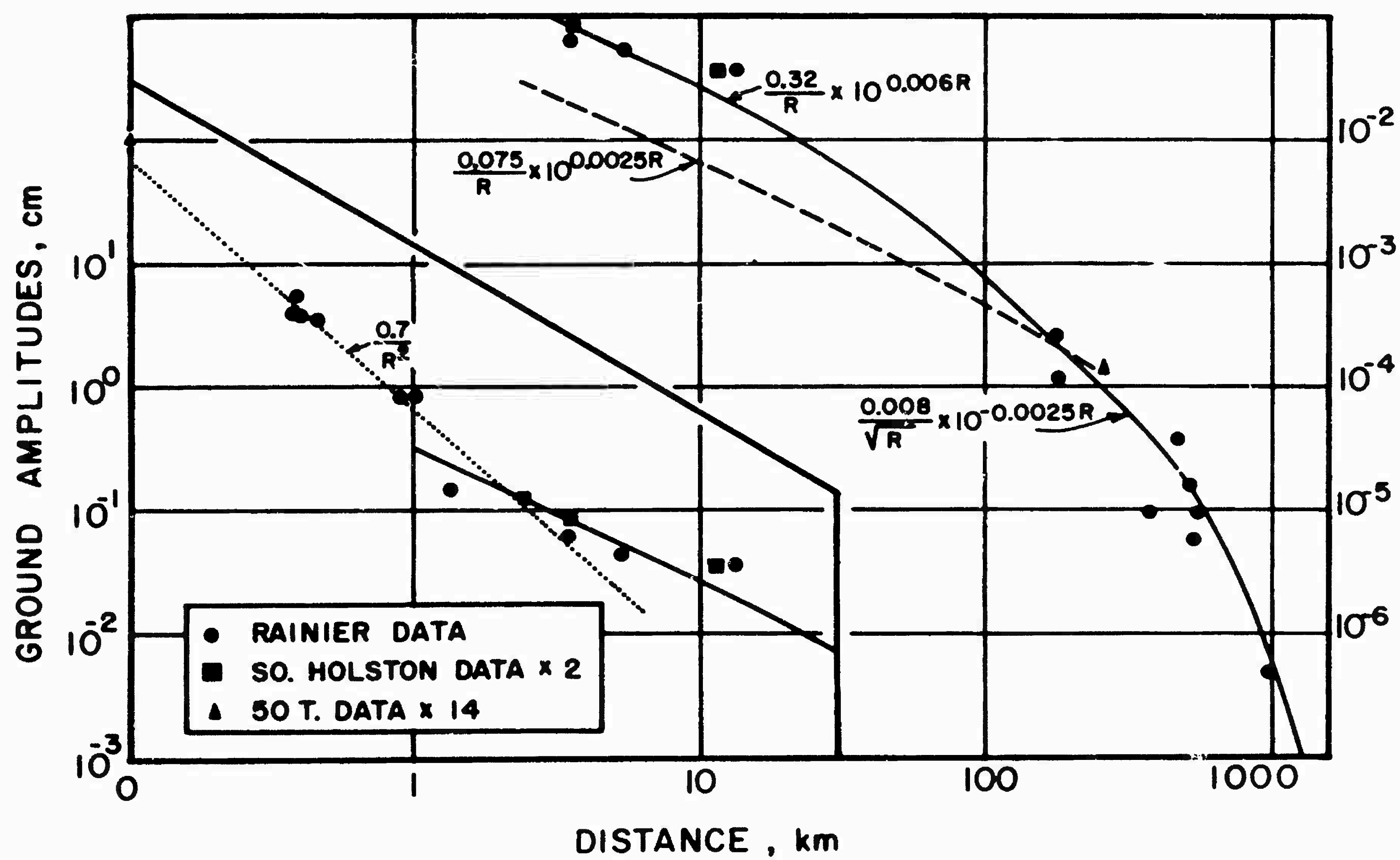


Fig. 4.1 Revised displacement attenuation formulas. For use in extrapolation, values from curves should be multiplied by $(W(tons)/1700)^{3/4}$.

4.4.2 South Holston Data

South Holston data entered on Figure 4.1 are probably misleading. If wave periods are to be considered, the points indicated by squares should be by a factor of 3 higher than are represented, since maximum amplitudes are associated with periods of 0.3 sec or so. It should be noticed that amplitude decrease is linear with distance, with no attenuation by absorption, or, if absorption is present, attenuation is somewhat less than linear, indicating that the energy under study has been trapped in the sedimentary rock of the area. This is possible since the source and the recordings were in practically the same formations.

4.5 DISCUSSION OF ACCELERATION ATTENUATION

The empirical relationship in formula (2.1) fits nearby and teleseismic data quite well. No attempt therefore will be made to refine it by using formulas based on energy absorption and distribution.

4.6 SEISMIC ENERGY AT THE SOURCE

Seismic energy is defined as the energy that leaves the source in the form of elastic waves in the rock. Since the Rainier explosion was nearly 1000 feet under the surface, we will assume for close-in measurements a spherical wave front leaving the source in all directions, and with uniform energy dissipation. We will use a rock density of 2.5, a speed of 2.4 km/sec, and a value for surface or near surface amplitudes twice that of the confined amplitudes. We will assume an absorption constant of 0.4 per km from 0 to 3 km and 0.005 per km beyond 3 km. Actually it is probably higher than this within the first thousand feet and somewhat lower at 2 to 3 km, but, until later refinements are made, this assumption seems to serve adequately for empirical purposes. Using these figures $\rho v \pi^2/2 = 30 \times 10^5$ and the area of the wave front is $4\pi R^2 \times 10^{10}$. A second calculation will assume a hemispherical wave front and lesser values for ρ and v, so that $\rho v \pi^2/2 = 20 \times 10^5$ and the area of the wave front is $2\pi R^2 \times 10^{10}$. No energy scatter other than absorption will be assumed. Pertinent data from close-in stations and the calculated logarithm of the source seismic energy are listed in Table 4.1.

The median values of exponentials 18.1 and 18.6 are equivalent to earthquake magnitudes of 4.6 and 4.9. Earthquakes of lesser magnitudes are felt at distances somewhat greater than 2.5 miles. However, direct comparison with earthquakes is not entirely valid, since the energy calculations were based on high absorption near the source. In the calculations

TABLE 4.1 SEISMIC ENERGY CALCULATIONS FROM DISPLACEMENT DATA

Station	R, km	$\Sigma A^2/T$	$E_s \times 10^5$ max.	10^{kR}	Log E max est.†	Log E min est.†
6003.01	5.38	0.033	1.00	16.4	18.77	18.29
.02	3.53	0.036	1.08	16.0	18.45	17.97
.03	1.34	0.30	9.00	3.44	17.85	17.33
.04	0.90	3.5	105	2.29	18.38	17.90
.05	0.41	40	1200	1.46	18.57	18.09
.06	0.39	52*	1560	1.43	18.62	18.14
.07	0.46	50*	1500	1.53	18.69	18.21
.08	0.38	34*	1020	1.42	18.41	17.93
.09	1.015	4.4	1.32	2.55	18.64	18.16

* Scaled in detail from records.

† Median Log E = 18.6 max est., 18.1 min est.

Note: High frequency waves were not included in the above calculations. Since energy attenuation of higher frequencies is probably more rapid relatively, 18.6 for the value for Log E is probably more realistic than the lower value.

high absorption, by assumption, ceases at 3 km from the source. The wave at this distance contains only 6 or 7 per cent of the estimated source energy. If the wave front at this distance is to be used for comparison purposes with earthquake magnitudes, log E is reduced by about 1.2, leaving 17.4 and 16.9 for maximum and minimum exponential values, corresponding to and earthquake of magnitude near 4.0. This is perhaps a more realistic figure.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

a. The Rainier underground nuclear explosion was successfully recorded by strong-motion seismographs at distances ranging from about 1250 feet out to 13.6 km.

b. It was recorded by station seismographs as far as Fairbanks, Alaska, with possibly a shadow area from 2000 to 3000 or more km. At 1000 km, the amplitude of P and surface waves was about 5×10^{-7} cm.

c. Strong-motion data indicate source seismic energy of $10^{18.1}$ to $10^{18.6}$ ergs, which agrees with estimates using the Gutenberg-Richter magnitude formula. Magnitude estimates were 4.6 to 4.9 at the source or about 4.0 in a shell 3 km from the source.

d. Acceleration attenuation according to the formula

$$a = \frac{25 \times 10^5 g}{D^2 (ft^2)}$$

fits all the observed data with reasonable accuracy.

e. Energy attenuation by absorption about 1200 feet or so from the source is high: at the rate of about $10^{0.4}$ per km. From 3 to 1000 km it is about $10^{0.005}$ per km. Estimated amplitude (ground displacement) decreases about as the square of the distance from 0.3 to 3 km and linearly with the distance with an absorption factor of $10^{0.006}$ per kilometer from 3 to 100 km. From 180 to 1000 km, the greatest amplitudes are in 1-sec-period S or surface waves which attenuate as the square root of the distance with an absorption factor of $10^{0.0025}$ per km.

f. Ground shock waves were barely felt at distances of 2.5 miles.

5.2 RECOMMENDATIONS

a. Future tests similar to Rainier should be monitored by strong-motion and teleseismic seismographs.

b. The spread of strong-motion seismographs should be about as with the Rainier spread except that distances from 0.4 to 5 km should have more uniform distribution.

c. Paper speeds for accelerograph recorders should be about 3 inches per second or more and about 1 inch per second for displacement meter recorders.

d. Sensitivities and magnifications should be according to par. 5.1 d and Figure 4.1, multiplied by the factor $(W/1700)^{3/4}$, where W is the TNT equivalent in tons.

e. For scaling purposes, at least three of the strong-motion seismographs should be as nearly as possible equidistant from all shots to be fired in the same area, or if two areas within a few miles of each other are to be used, at least two of the more distant stations (not including a station located on deep alluvium) should be equidistant from the two areas.

f. For scaling purposes a displacement-type seismograph should be located on rock 15 to 30 miles east of the shot area. Loop vane Survey vibration meters are recommended.

g. Suggested additional teleseismic work includes:

(1.) One teleseismic station should be located in each quadrant at distances about 50, 100, 150, and 200 miles from the test area. Portable moving-coil seismographs, e.g., Wilson-Lamison, that weigh about 25 lb each should suffice.

(2.) Additional coverage with highly sensitive short-period seismographs in the 16° to 30° range, especially for shots of 5 kt or greater.

(3.) Long- and short-period seismographs one each 100 miles out to 30° or so.

(4.) Time control at each station sufficient to ascertain world time within 0.1 sec.

(5.) Instruments to be calibrated so that ground motion within 20% may be ascertained.

(6.) Experiment with high-frequency exploration equipment out distances to 30°.

h. Future underground detonations of 50 to 100 times the size of the Rainier charge can be safely performed in the same or similar areas, insofar as the seismic effects are concerned.

i. For scaling purposes and otherwise, a shot within the dolomite beneath the tuff, if at all feasible.

REFERENCES

1. W. K. Cloud and D. S. Carder, "The Strong-Motion Program of the Coast and Geodetic Survey," Proceedings of the World Conference on Earthquake Engineering, pp. 2-1 to 2-10 (1956).
2. D. E. Hudson, "Response Spectrum Techniques in Engineering Seismology," Proceedings of the World Conference on Earthquake Engineering, pp. 4-1 to 4-12 (1956).
3. L. Don Leet, "Blasting Vibration Effects," The Explosives Engineer, March-April (1957).
4. Beno Gutenberg and C. F. Richter, "Earthquake Magnitude, Intensity, Energy, and Acceleration," Bull. Seism. Soc. Am. 46, 105-145 (1956).

APPENDIX

TABLE A.1 STATION COORDINATES AND ELEVATIONS (PROJECT 26.4d)

Station	Coordinates		Elevation
	N	E	Feet
01	889,049.83	652,507.41	5038.55
02	890,006.95	646,497.26	5353.04
03	890,482.13	639,350.78	6010.64
04	889,314.90	637,670.47	6447.80
05	889,646.16	635,969.87	6714.09
06	889,876.56	634,381.41	7501.75
07	889,645.85	634,193.61	7503.83
08	890,538.08	634,072.44	7441.00
09	890,361.80	631,769.82	7379.44
7.2a2 (North)	881,275.88	678,575.95	4284
Surface Zero	890,571.02	635,003.48	7514.44
Underground Zero	"	"	6614.93

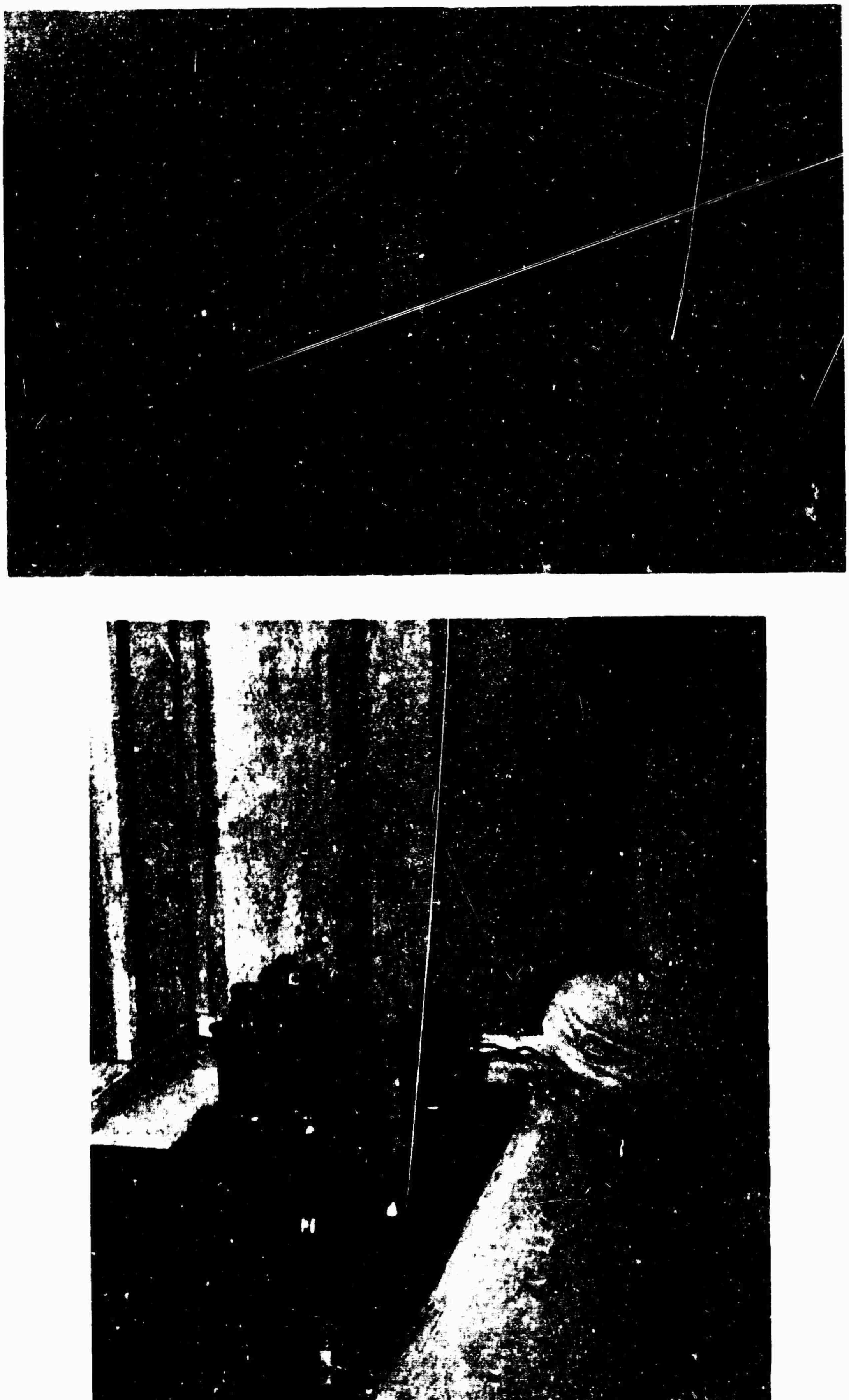
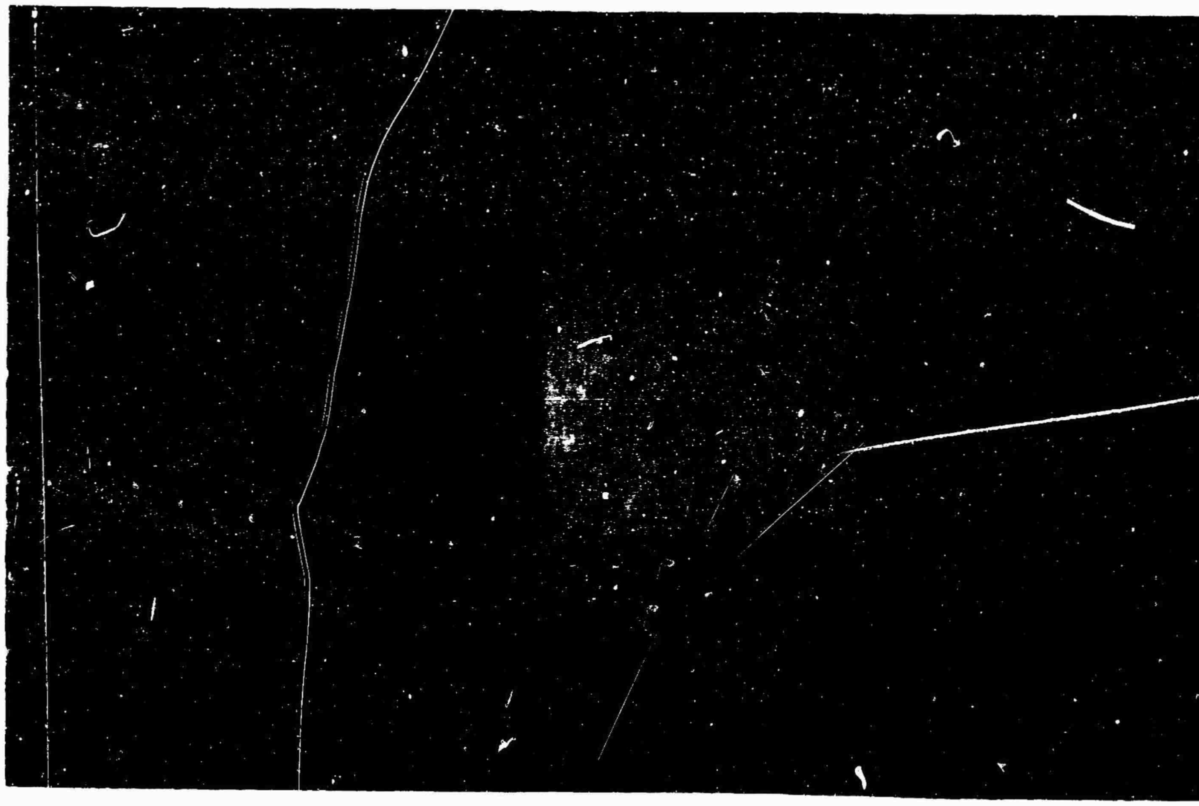


Fig. A.1 Instrument shelter at Station 12-26.4-6003.02. Door faces away from zero. Lower photo shows the C & GS strong-motion seismograph.



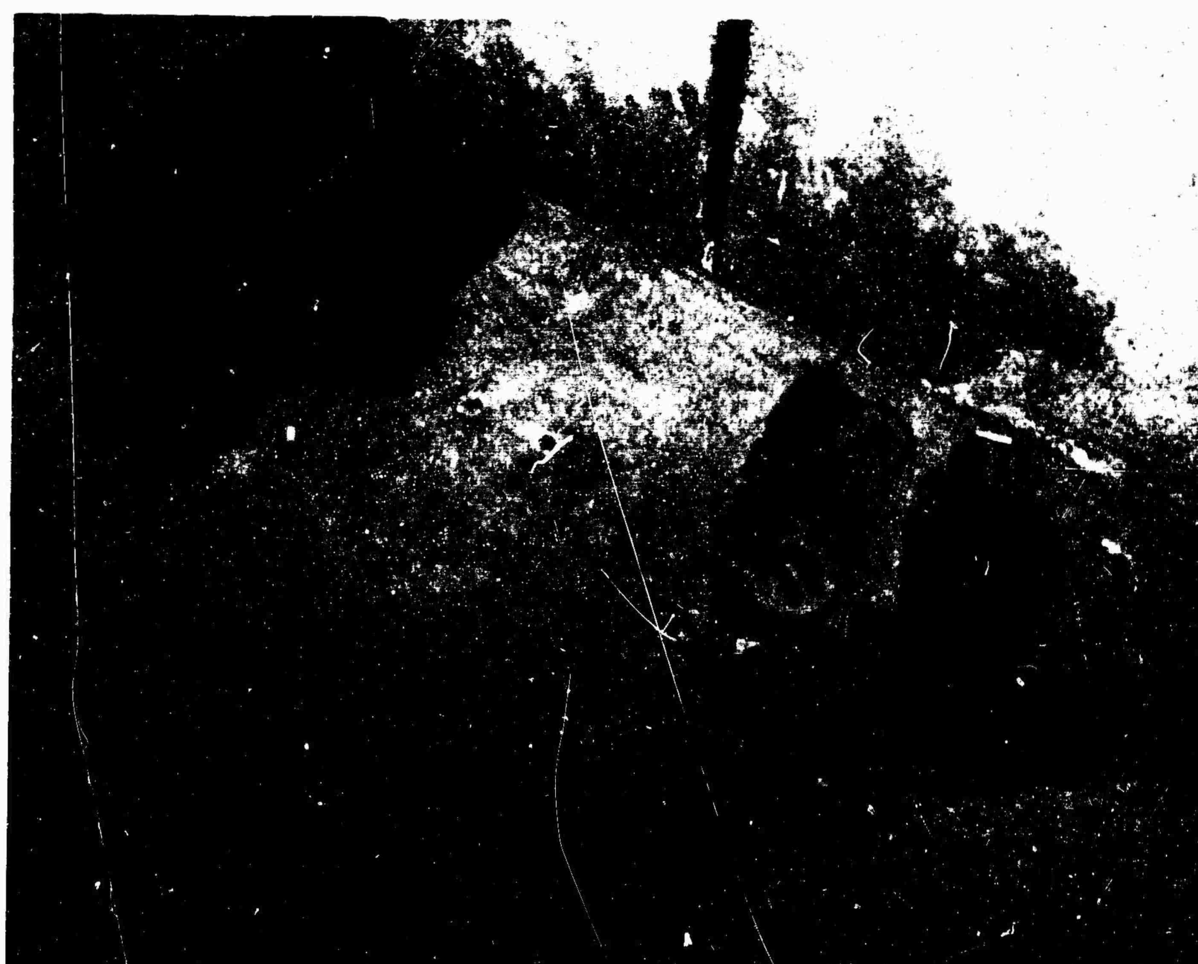


Fig. A.2 Instrument shelter at Station 7.2a (North). Door faces zero. Lower photo shows instrumentation.

Fig. A. 3 Instrumentation at Station 12-26.4-6003.05. Sandia equipment in background. Camera facing away from zero.

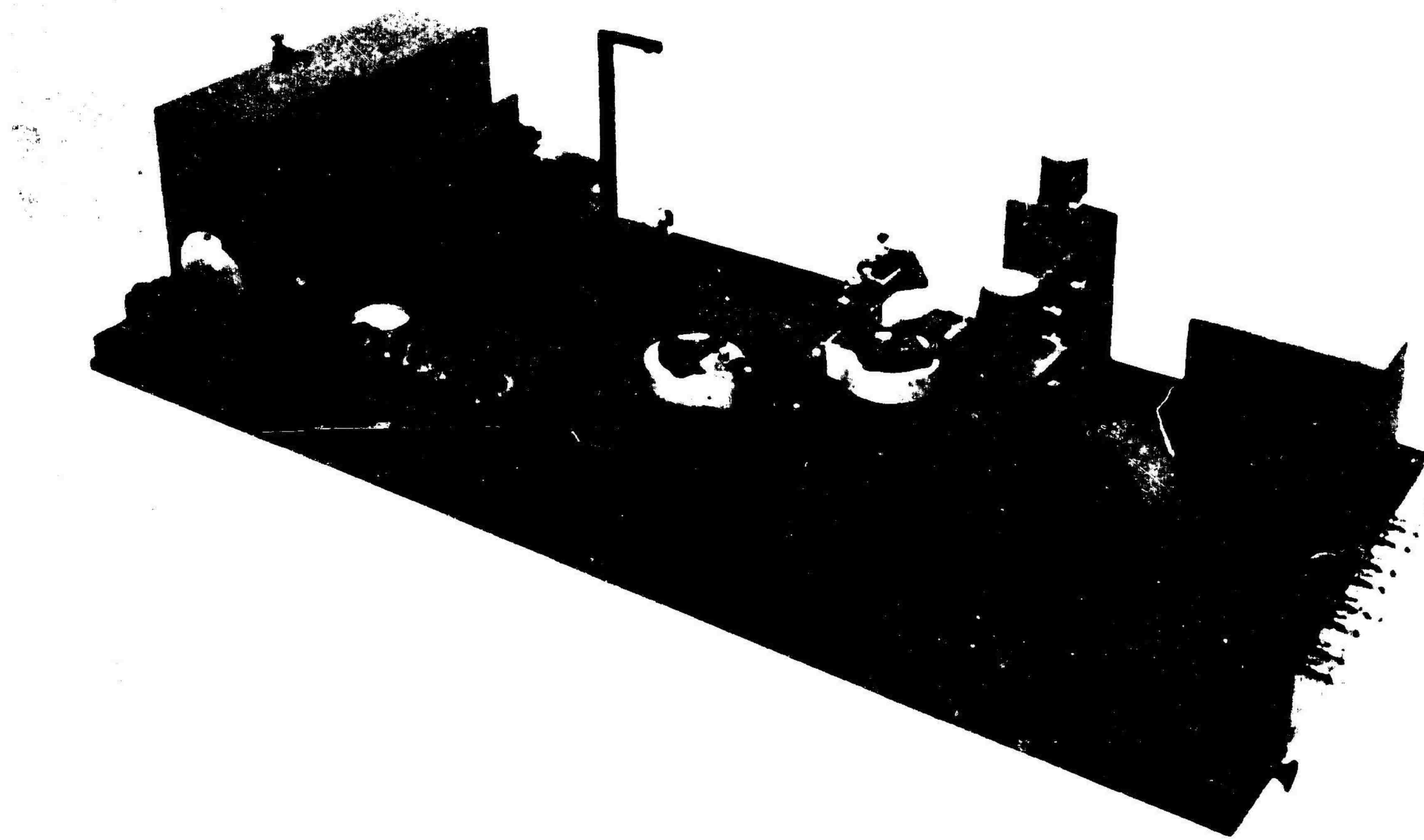


Fig. A. 4 Photo of Coast and Geodetic Survey strong-motion seismograph.

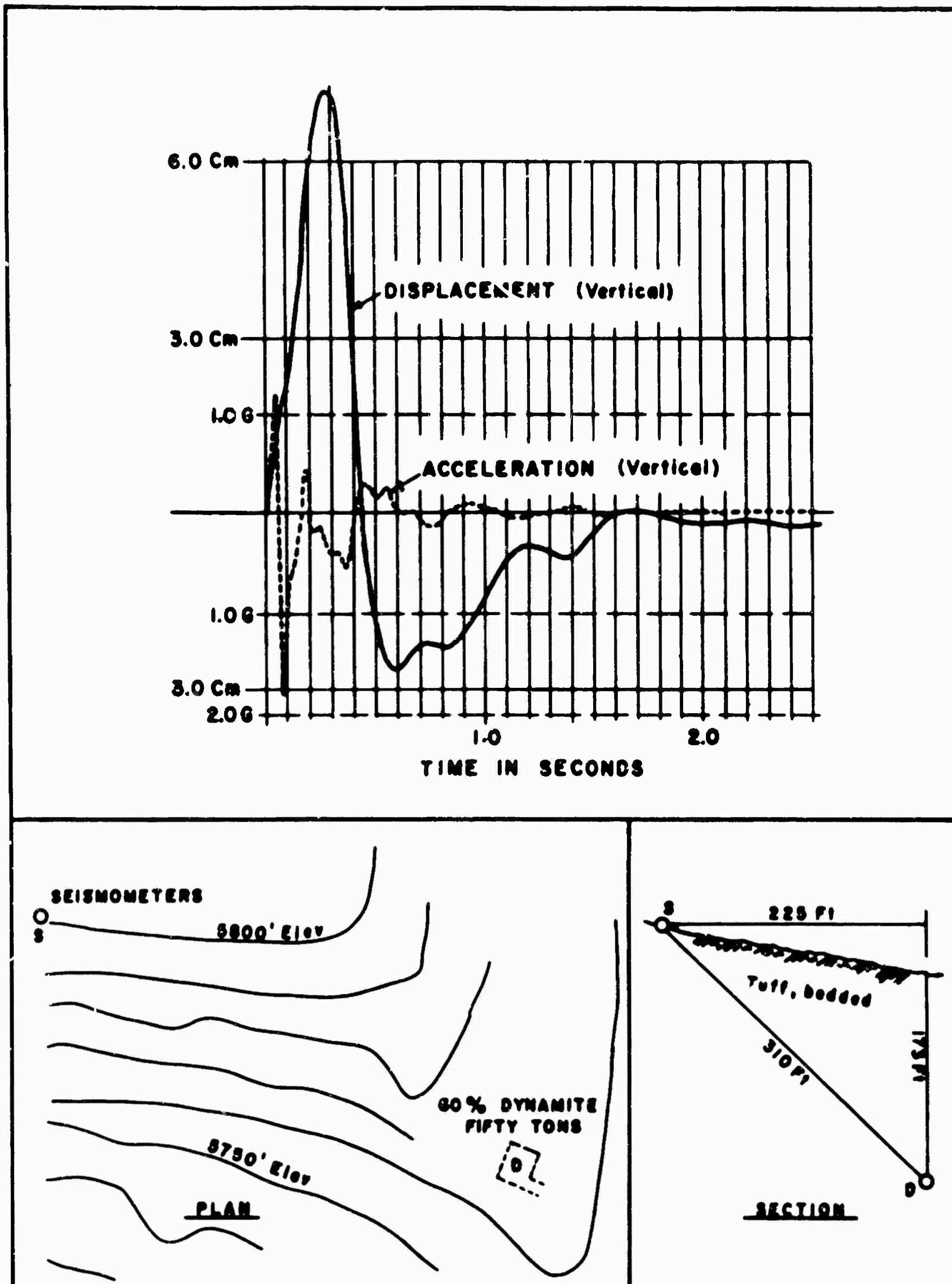


Fig. A. 5 Location and tracing record of experimental 50-ton high-explosive shot.